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An Embedded Grid Formulation Applied to Delta Wings

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An embedded-grid algorithm for the Euler/Navier-Stokes equations is developed and applied to delta wings at high angles of attack in low-speed flow. The Navier-Stokes code is an implicit, finite-volume algorithm, using flux-difference-splitting for the convective and pressure terms and central differencing for the viscous and heat transfer terms. Calculations are compared with detailed experimental results over an angle of attack range up to and beyond the maximum lift coefficient, corresponding to vortex breakdown at the trailing edge, for a delta wing nominally of unit aspect ratio. The results indicate that the overall flowfield, including surface pressures, surface streamlines, and vortex trajectories, can be simulated accurately with the global grid version of the present algorithm. However, comparison of computed velocities and vorticity with experimentally measured off-body values at an angle of attack of 20.5 degree indicates the core region is substantially more diffuse in the computations than that measured with either a five-hole probe or a laser velocimeter.

Embedded grids, used in the present work to improve the numerical discretization in the core region, are formulated within the framework of the implicit, upwind-biased multi-grid algorithm. Structured levels of local nested refinements are made. The refinements, which should be based on the local truncation error of the solution, are currently based on the location of the vortex core trajectory. The embedded grid boundary data are determined through linear interpolation of the coarser underlying grid. The values of flow variables in the coarser grid cells underlying finer grids are determined by a volume-weighted restriction of the finer grid values. To compensate for the limited extent of the implicit operators in the embedded grids, each level of grid refinement uses corrections from coarser grids, which can be either embedded or global grids, to accelerate the convergence to the steady state of the embedded blocks.

Three-dimensional results for both Euler and Navier-Stokes calculations are shown, with up to 3 levels of embedded refinement. The embedding procedure was effective in eliminating a crossflow secondary separation produced in the Euler solutions on coarse grids. The core velocities in the Euler solutions are substantially higher than in the viscous solutions and in both, the embedded grids can efficiently reduce the numerical diffusion in the flowfield. The computed core velocities in the viscous calculations are increased on the embedded grids but are lower than the measured values with the grids used in the present study.

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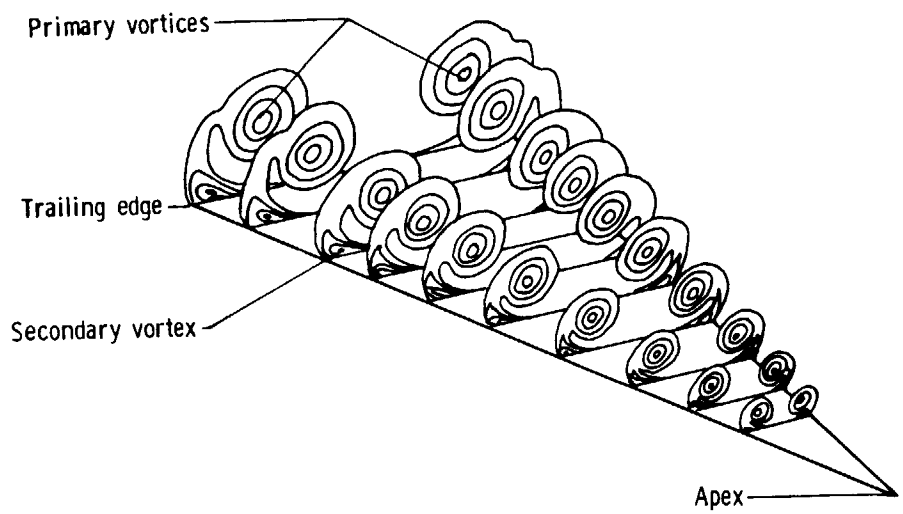
INTRODUCTION

Motivation :

Performance and stability of aircraft at high angles of attack are dominated by the nonlinear interaction of shed vortices

Present objective :

Compare predictions of Navier-Stokes code with detailed experimental data for delta wings with both global and embedded grid schemes

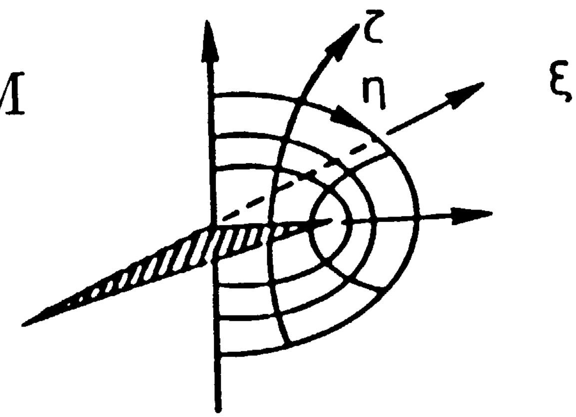


OUTLINE OF PRESENTATION

- Introduction
- Global grid scheme
    - Computational algorithm
    - Comparisons with experiment
- Embedded grid scheme
    - Spatial differencing
    - Time advancement
- Computational results
    - Euler
    - Navier-Stokes
- Concluding remarks

GLOBAL GRID ALGORITHM

Upwind-biased Navier-Stokes code CFL3D



$$\frac{\partial \widehat{Q}}{\partial t} + \frac{\partial \widehat{F}}{\partial \xi} + \frac{\partial \widehat{G}}{\partial \eta} + \frac{\partial (\widehat{H} - \widehat{H}_v)}{\partial \zeta} = 0$$

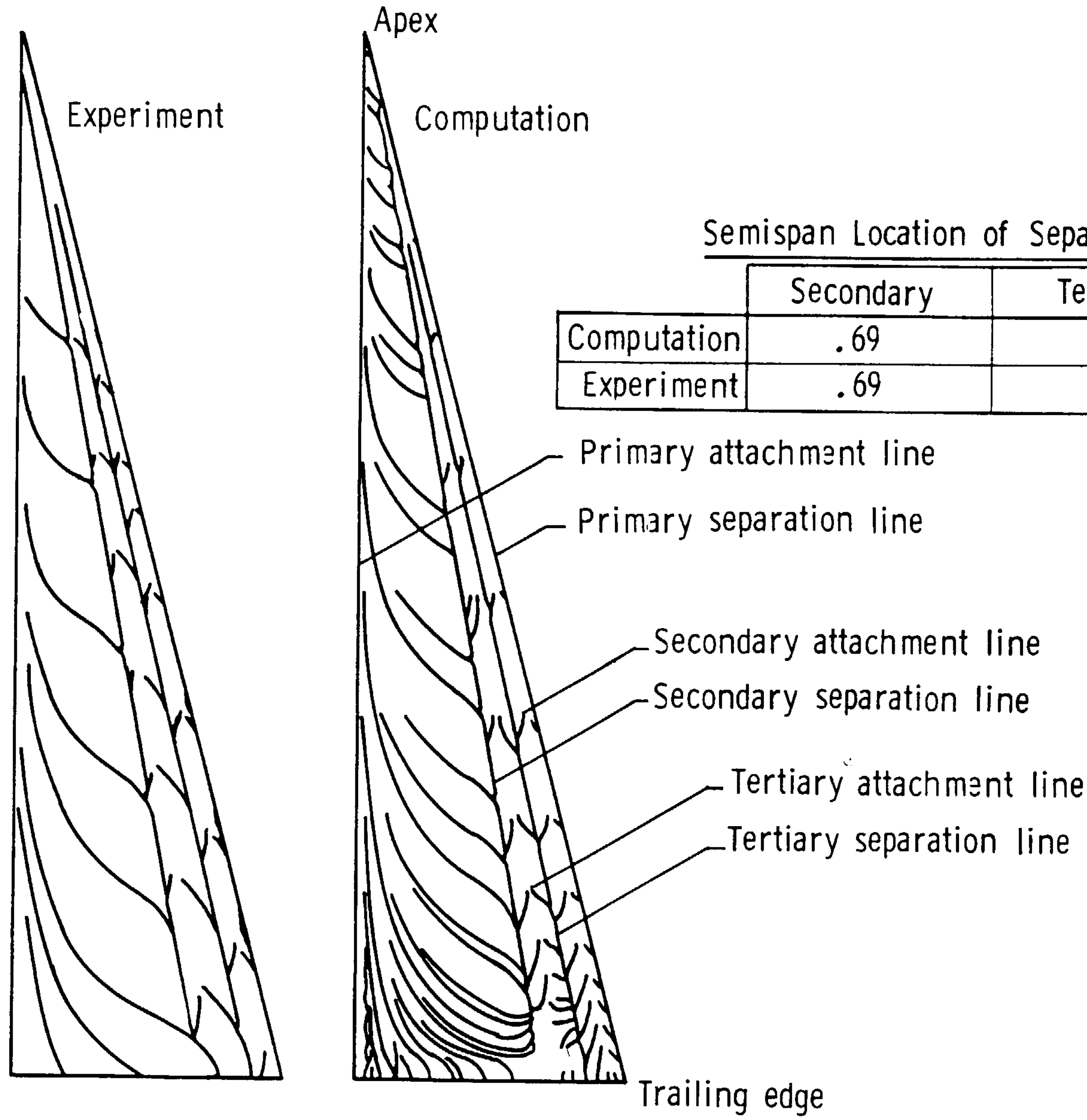
- Time-dependent conservation law form of compressible Navier-Stokes equations
- Implicit (diagonalized) time advancement algorithm
- Upwind-biased spatial differencing
  - o Flux difference splitting for convective/pressure terms
  - o Central differencing for shear stress/heat transfer terms
- Thin-layer with algebraic turbulence model
- Semi-discrete finite-volume implementation
- Zonal (patched) grids

COMPARISONS WITH EXPERIMENTS

Delta wings at high alpha in low speed flow

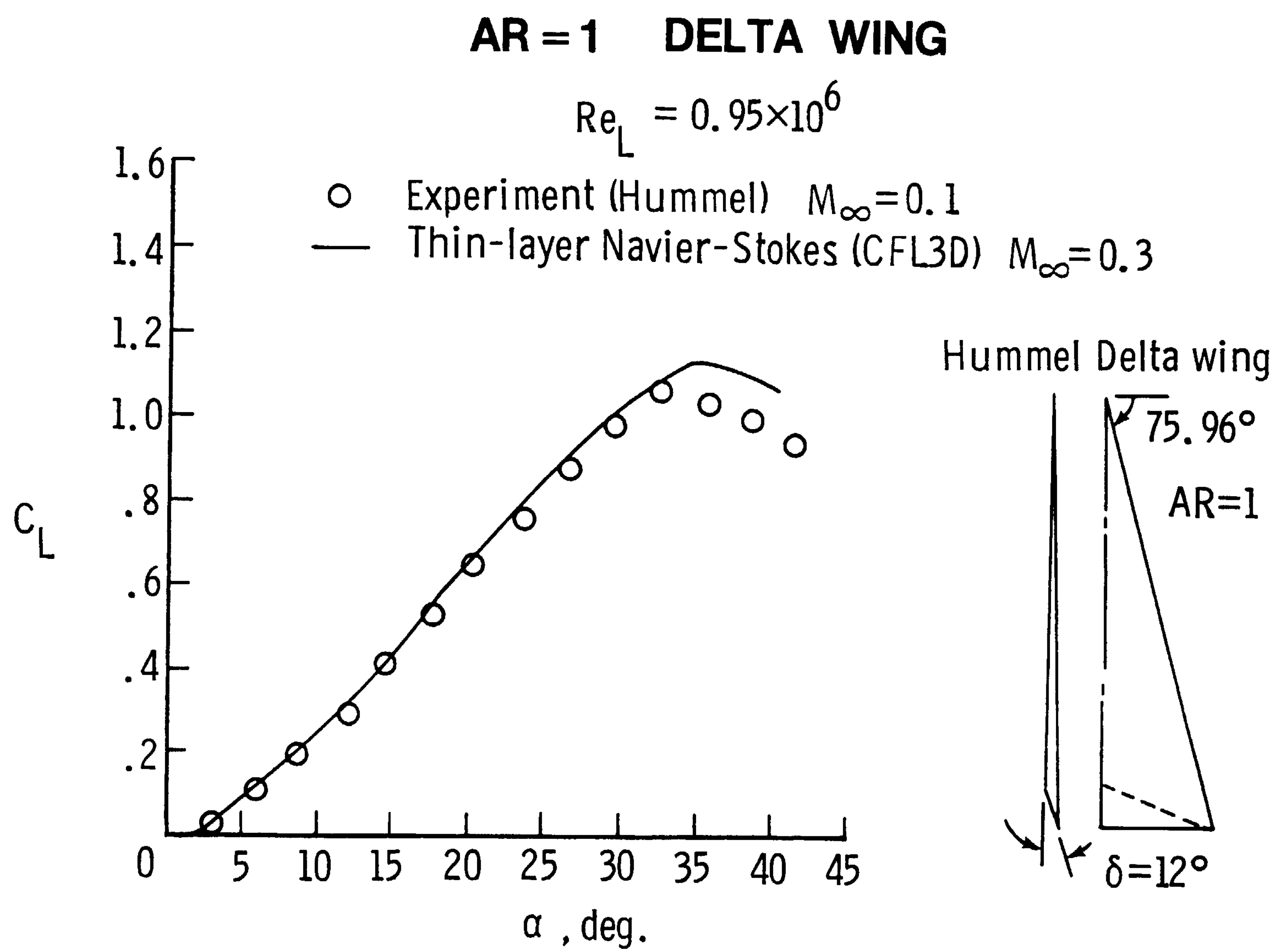
- Hummel (DFVLR) AR=1 wing
  - $R_L = 0.95 \times 10^6$
  - Force and moment
  - Surface oil flows
- Kjelgaard and Sellers (BART) $\Lambda = 75°$wing
  - $R_L = 0.5 - 1.5 \times 10^6$
  - Surface oil flows
  - Flowfield measurements (5-hole probe / LDV)

SECONDARY AND TERTIARY SEPARATION LINES

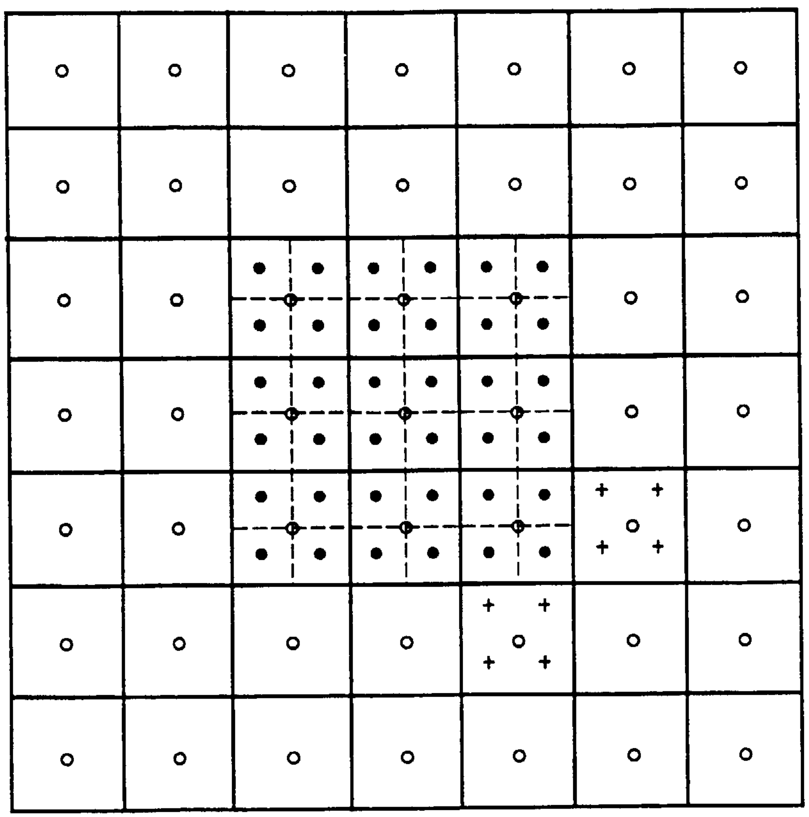


Semispan Location of Separation Lines

	Secondary	Tertiary
Computation	.69	.87
Experiment	.69	.88


AR = 1 DELTA WING
Re_L = 0.95×10^6
Experiment (Hummel) M∞=0.1
Thin-layer Navier-Stokes (CFL3D) M∞=0.3
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
C_L
5 10 15 20 25 30 35 40 45
α, deg.
Hummel Delta wing
75.96°
AR=1
δ=12°

Embedded Grid Scheme

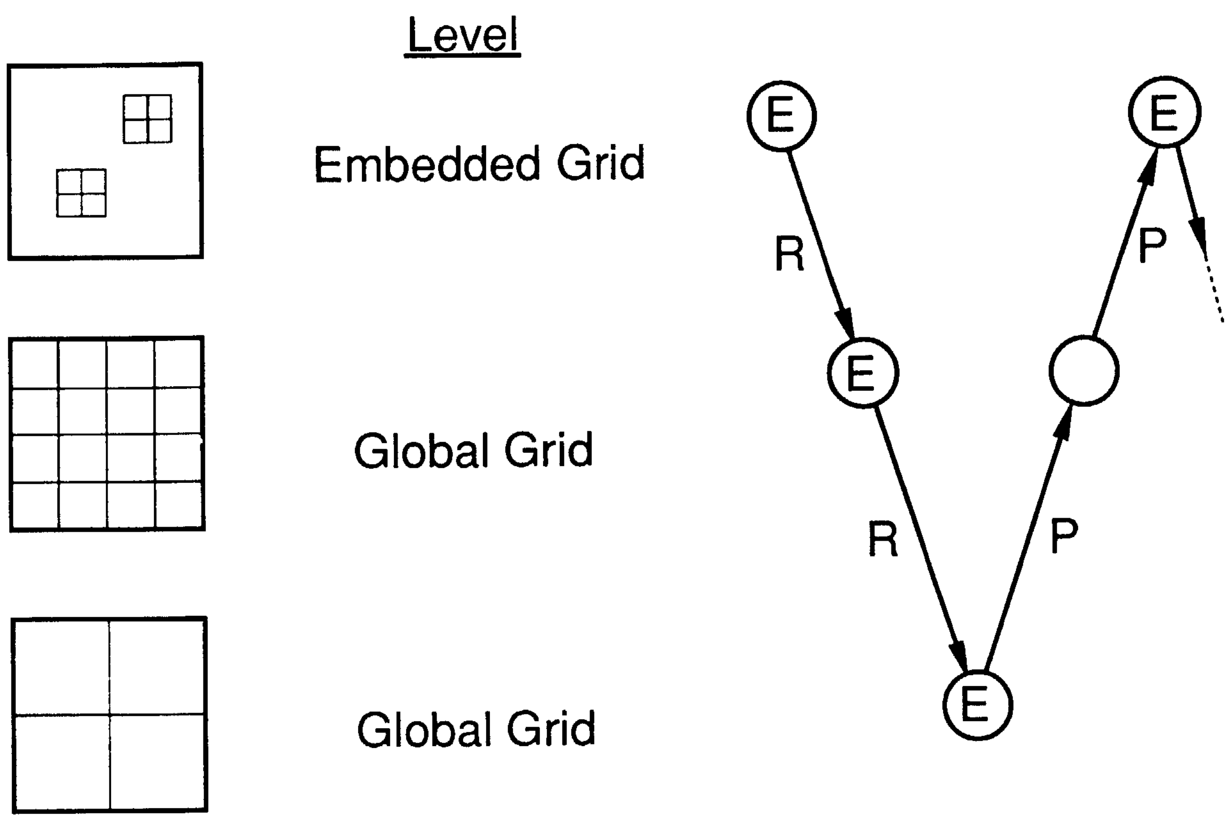


—— Coarse grid

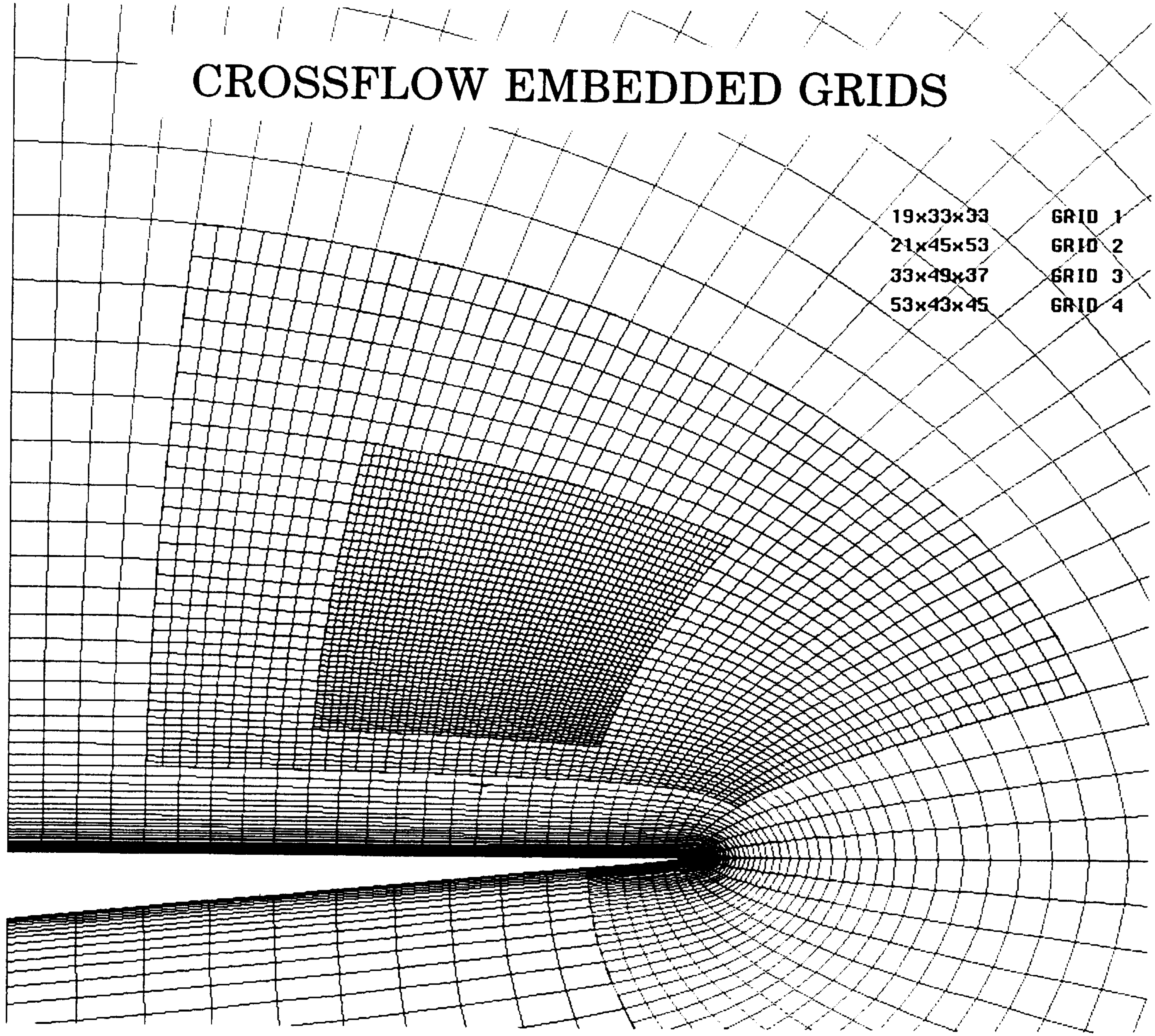
------ Fine grid

- Volume-weighted restriction of finer grid to coarser grid cells
- Linear interpolation for projections of finer grid cells into coarse grid

Embedded Grid Scheme

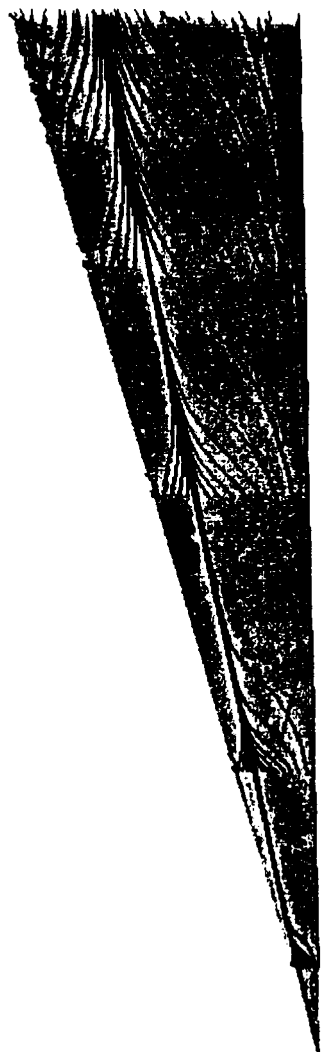


E: Navier-Stokes Calculation
R: Restriction of Residual and Q
P: Prolongation of Correction

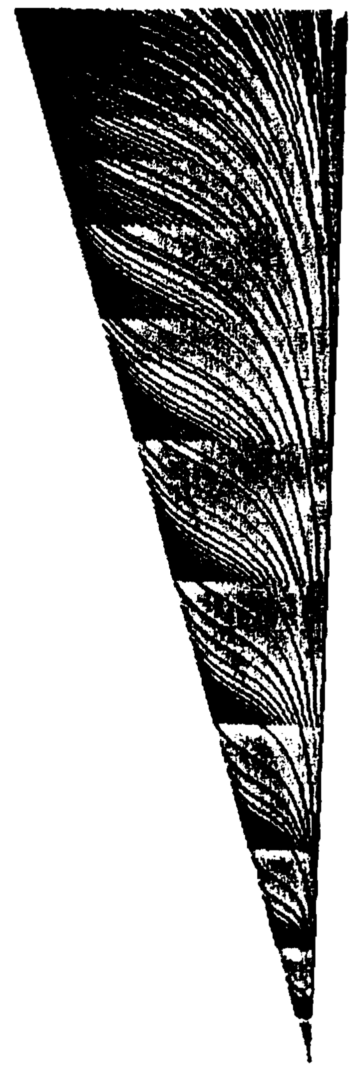

CROSSFLOW EMBEDDED GRIDS
19x33x33 GRID 1
21x45x53 GRID 2
33x49x37 GRID 3
53x43x45 GRID 4

PARTICLE TRACES

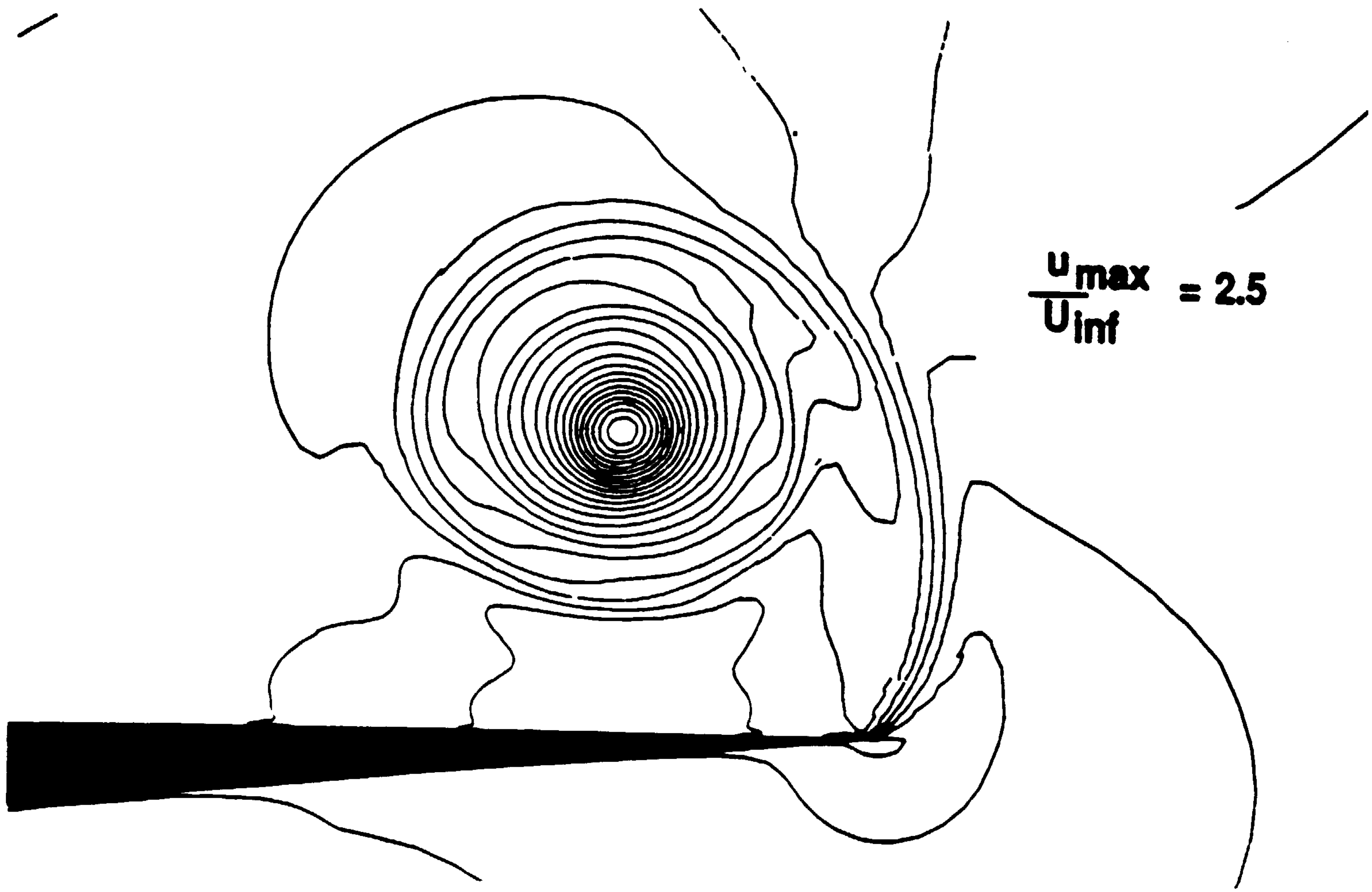
33x33x19 Mesh



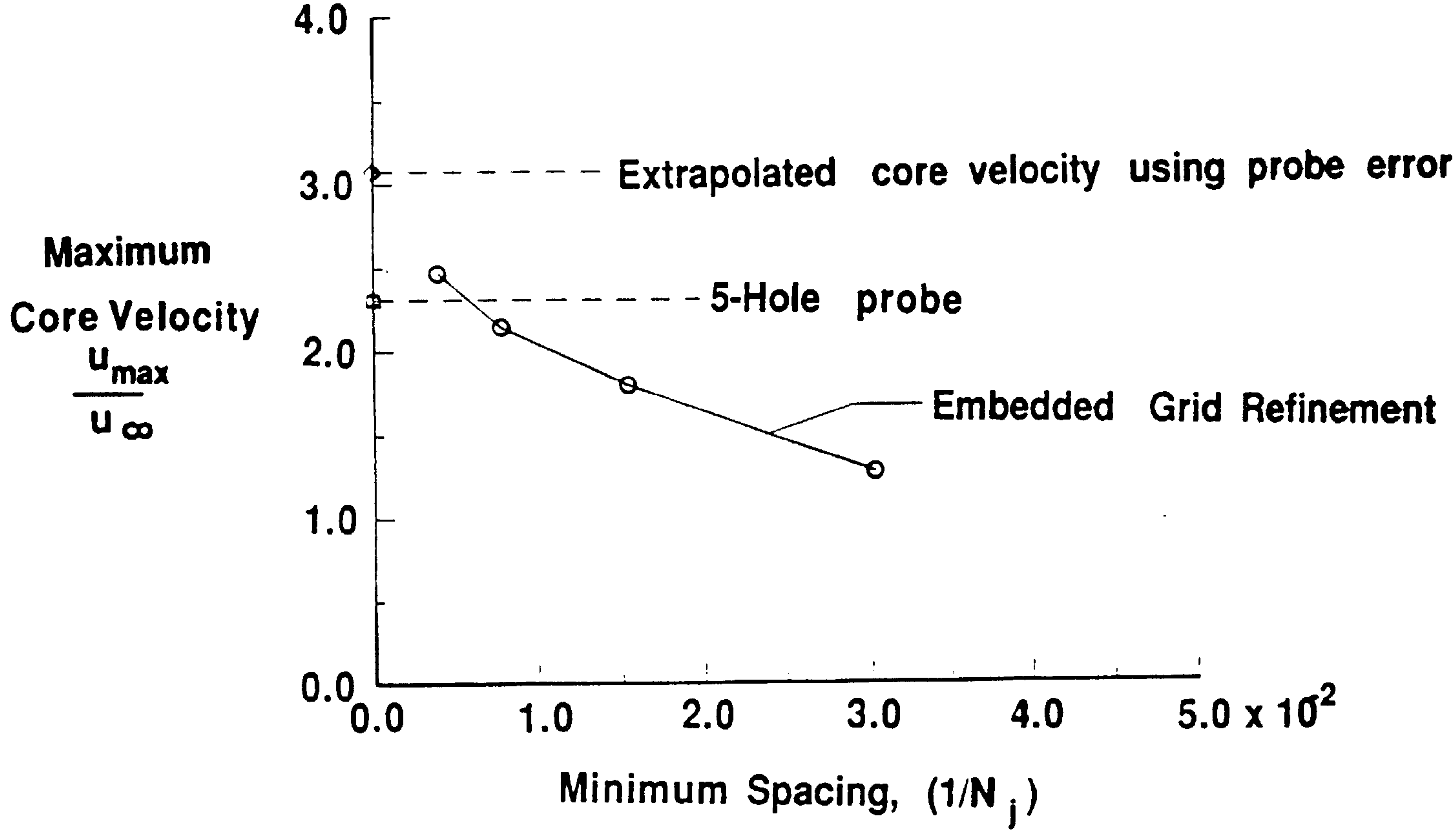
w/Grid Embedding



EULER SOLUTION FOR 76 DEGREE DELTA WING
u velocity component



GRID REFINEMENT EFFECT
x/L = 0.7



3-D NAVIER STOKES RESULTS

$\alpha = 20.5\,^\circ$; $\Lambda = 75\,^\circ$; $R_L = 0.5 \times 10^6$

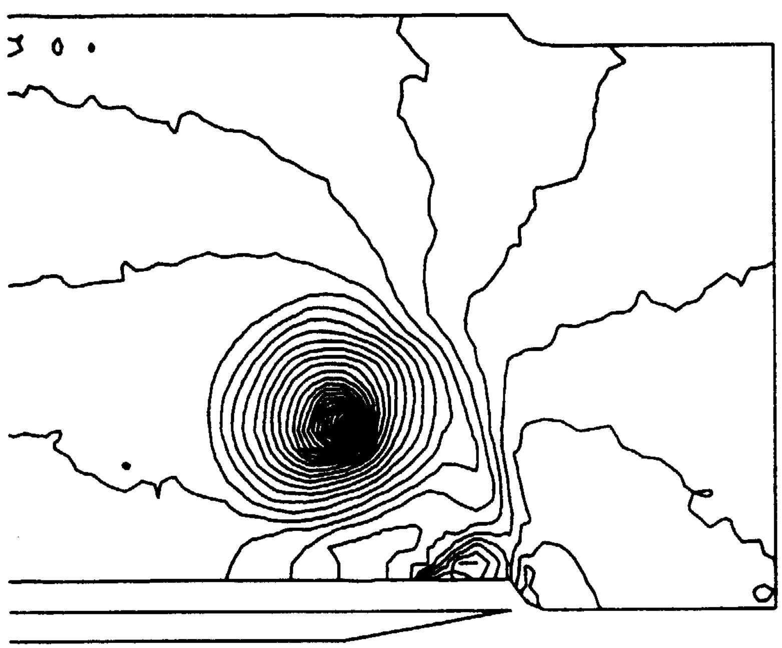
Mesh	Grid points	u_{max}/u_∞ @ x/L = 0.7
33x33x19 global	20,691	1.20
33x33x19 global w/ 3 embedded levels	233,160	1.80
65x65x37 global	156,325	1.55
65x65x37 global w/ 1 embedded level	512,770	1.92

STREAMWISE VELOCITY CONTOURS

x/L = 0.7 ; α = 20.5

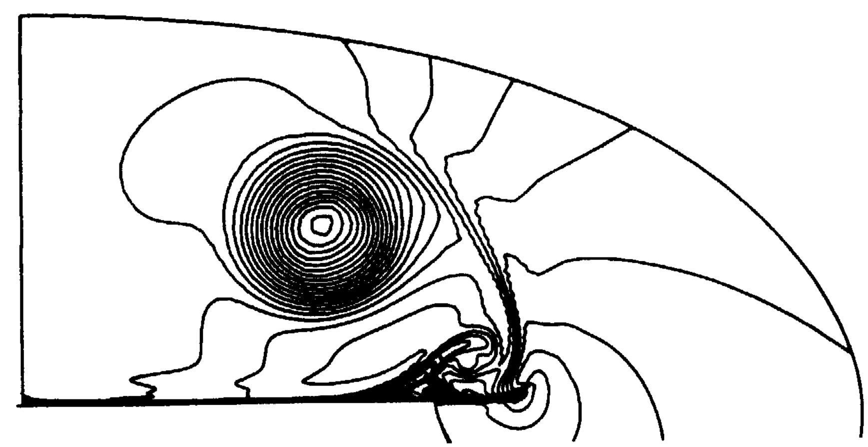
Experiment

$u_{max}/u_{\infty} = 2.25$



Navier-Stokes

$u_{max}/u_{\infty} = 1.92$



CONCLUDING REMARKS

- Global grid algorithm predicts overall flow topology and surface characteristics of delta wings in good agreement with experiment
    - Force and moment
    - Surface oil flows
    - Vortex trajectories
- Embedded grid algorithm provides efficient way to predict local off-surface flows
    - Vortex core velocities
    - Downstream interactions